AD-A031 849 CALIFORNIA UNIV BERKELEY DEPT OF PHYSICS F/G 9/5
SUPERCONDUCTING DEVICES FOR MILLIMETER AND SUBMILLIMETER WAVELE--ETC(U)
OCT 76 P L RICHARDS N00014-75-C-0496

UNCLASSIFIED NL

| OF |
AD
A031849

END
DATE
FILMED
12-76

ADA031849

12

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) (6) SUPERCONDUCTING DEVICES FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS.		5. TYPE OF REPORT & PERIOD COVERED Technical - 2/1/76 to 1/31/77
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) (10) P. L. Richards		8. CONTRACT OR GRANT NUMBER(s) (15) N00014-75-C-0496
9. PERFORMING ORGANIZATION NAME AND ADDRESS Professor P. L. Richards, Department of Physics, University of California, Berkeley, Calif. 94720		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS NR ~~319~~-055
11. CONTROLLING OFFICE NAME AND ADDRESS Office of Naval Research, Physics Program Office, Arlington, Virginia 22217		12. REPORT DATE (11) October 1976
		13. NUMBER OF PAGES 16 (12) 17p.
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) (9) Technical rept. 1 Feb 76-31 Jan 77,		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Unlimited

D D C
RECEIVED
NOV 11 1976
C

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

Presented at the International Conference on Quantum Interference Devices, Berlin, Germany. October 4-8, 1976.
To be published (H. D. Hahlbolm & H. Lübbig, Eds. - Walter de Gruyter, Berlin - New York, 1977).

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Microwave devices, superconductivity, Josephson effect.

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

Josephson junctions are highly nonlinear and respond up to infrared frequencies. A wide variety of high frequency applications have been explored. In addition, several high frequency superconducting devices are being developed which do not use the Josephson effect. These include a superconducting version of the Schottky barrier diode for use as a heterodyne mixer and a video detector, and also a composite superconducting bolometer. In this review, ~~we will discuss~~ the state of development of superconducting mixers, detectors, and parametric amplifiers at microwave, — over

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

071970

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. millimeter, and submillimeter wavelengths is discussed. Emphasis will be placed on developments which have taken place since 1974 when a previous review was circulated.

SQUID - Superconducting Quantum Interference Devices and Their Applications, H. D. Hahlbohm and H. Lübbig, Eds. (Walter de Gruyter, Berlin - New York, 1977) to be published.

SUPERCONDUCTING DEVICES FOR MILLIMETER AND SUBMILLIMETER WAVELENGTHS†

P. L. Richards
Department of Physics, University of California, Berkeley, California 94720

Josephson junctions are highly nonlinear and respond up to infrared frequencies. A wide variety of high frequency applications have been explored. In addition, several high frequency superconducting devices are being developed which do not use the Josephson effect. These include a superconducting version of the Schottky barrier diode for use as a heterodyne mixer and a video detector, and also a composite superconducting bolometer. In This review, we will discuss the state of development of superconducting mixers, detectors, and parametric amplifiers at microwave, millimeter, and submillimeter wavelengths. Emphasis will be placed on developments which have taken place since 1974 when a previous review was circulated[1].

Super-Schottky Mixer

In an ordinary Schottky barrier diode, thermally excited carriers give an I-V curve of the form $I = I_o \exp(SV)$, where $S = e/kT$ at room temperature. When such diodes are cooled, the S parameter usually saturates at a few times the 300 K value, and non-thermal noise is seen. Although not understood in detail, these effects are usually ascribed to leakage currents. A version of the Schottky diode has been developed[2] to obtain large S-values at low temperatures. It operates in the tunneling dominated region and is nonlinear because of the sharp energy gap structure on the superconducting density of states near the Fermi surface. The effect is essentially the same as quasi-particle tunneling in a superconductor-insulator-normal metal junction.

The best super-Schottky performance demonstrated thus far has been with 5 μm diameter Pb spots on high conductivity p-type GaAs. Values of $S \approx 10^4\ V^{-1}$ have been obtained which are essentially equal to e/kT for the ambient pumped ^{4}He temperature. When care is taken to minimize leakage currents, the range of voltage ΔV over which S is constant can be sufficiently wide to obtain an intrinsic conversion loss $L_o < 5$ dB. Parasitic loss due

to the junction capacitance and the spreading resistance into the semiconductor contributes additional conversion loss. In experiments at 9 GHz, this additional loss L_p was ≈ 3 dB. Since L_p will increase as ω^2, it is a serious problem for higher frequency operation. It can be reduced by increasing the conductivity of the semiconductor, or by changing the conduction geometry. Improvement is possible by using a number of smaller diodes connected in parallel. Alternatively, a very thin semiconducting barrier, such as the etched single crystal Si barrier[3], could be used.

Experiments at 9 GHz on a 1.1 K super-Schottky have given a single sideband mixer noise temperature T_m = 6 K and a conversion loss of 7.5 dB. This is the lowest microwave mixer noise temperature ever reported. It demonstrates the high potential of these devices for low noise applications. The saturation level of this mixer has not been reported, but it can be estimated from given values of $S\Delta V$ = 6.5 and $S = 10^4$. A mixer with R_D = 400 Ohms should saturate severely at $P_S = P_{LO} \approx 10^{-9}$ W. This corresponds to a dynamic range of $< 10^4$ for T_m = 6 K and B = 1 GHz.

Super-Schottky Video Detector

Because of its high S-value at low temperature, the super-Schottky is an extremely quiet video detector[2]. In this application, the range of voltages over which S is constant is of importance only to the saturation level. Experiments at 9 GHz have shown an NEP of 5.4×10^{-16} W/$\sqrt{\text{Hz}}$ at a temperature of 1.06 K. This is the best microwave video NEP yet reported. Parasitic loss contributes more than a factor 2 to this NEP and would be increasingly important at higher frequencies, as is the case for the mixer application.

Josephson Effect Mixer With External Local Oscillator

A Josephson junction can be operated as an efficient mixer with a very small amount of local oscillator power (P_{LO}). The Josephson mixer therefore resembles the large S-value mixer discussed above. The details of its operation, however, are entirely different. If P_{LO} at a frequency $\omega_{LO}/2\pi$ is coupled to a Josephson junction, constant voltage steps with zero differential resistance appear which are separated by multiples of the volt-

age $V = \hbar\omega_{LO}/2e$. The steps are zero frequency beats between the AC Josephson frequency and the nth harmonic of ω_{LO}. The most useful type of Josephson mixer is biased with a constant current to a region between the $n = 0$ and $n = 1$ steps. In order to do this, it is necessary to use a type of Josephson junction such as a point contact, Dayem bridge, or small area tunnel junction, which has no hysteresis on the static I-V curve. The RF impedance of a Josephson junction biased in this way is real and nonlinear. It will serve as an efficient heterodyne down-converter for small RF signals.

The operation of a Josephson mixer can be most simply understood as follows: The total RF current, $I_{RF} = I_S + I_{LO}$ is amplitude modulated at ω_{IF}. If $I_{RF} \simeq I_o/2$, the height I_o of the zero voltage ($n = 0$) step is suppressed essentially linearly by I_{RF}, so is modulated at ω_{RF} by an amount proportional to dI_o/dI_{RF}. If the junction is biased with a constant direct current to a point between the $n = 0$ and $n = 1$ steps, the bias voltage swings at ω_{RF} by an amount proportional to $R_D(dI_o/dI_{RF})$. The conversion efficiency L^{-1} is thus proportional to $R_D(dI_o/dI_{RF})^2$.

The detailed performance of this mixer has been calculated using the resistively shunted junction (RSJ) model. At values of the normalized frequency $\Omega_{RF} = \omega_{RF}/2eI_cR << 1$, the conversion efficiency into a single sideband can be considerably greater than unity. The nonlinearity is of high order so that efficient harmonic mixing is possible.

If the frequency at which the Josephson mixer is operated corresponds to $\Omega > 1$, the conversion loss increases as Ω^2. Even for $\Omega >> 1$, the Josephson mixer retains an extraordinary capability as a harmonic mixer. Down-conversion from 891 GHz with an $\sim$ 1 GHz local oscillator has been observed[4]. The performance of Josephson effect fundamental mixers has been evaluated at least semi-quantitatively[5,6,7] at 36, 135, and 300 GHz using Nb point contact junctions with less than the full theoretical values of I_cR. In most of this work, $\Omega = 1$ corresponded to $\leq$ 300 GHz. The most complete results are at 36 GHz[5] where the measured conversion efficiency of 1.4 and the noise $T_m = 54$ K were in good agreement with analog computer calculations based on the RSJ model including thermal noise in the shunt resistance. Based on this model, it is possible to estimate the performance of Josephson effect mixers if we assume that non-hysteretic Nb junctions with

the full theoretical value of $I_c R$ will be available, so that $\Omega = 1$ at ~ 1 THz. The mixer contribution to the system noise temperature should be $T_m \approx 0.05$ to 0.1 times νT where ν is the frequency in GHz and T is the ambient temperature in Kelvin[8].

There are practical lower limits to the value of T_m/T which can now be reached for small Ω. The predicted proportionality $T_m/T \propto \nu$ occurs only if the RF source impedance is optimized. The optimum source impedance is $\ll R$ for $\Omega \ll 1$. Since it is difficult to transform the impedance of a free space wave below a few Ohms, optimum coupling to single junctions is hard to achieve for $\Omega \lesssim 0.3$. Consequently, the experimental values of T_m/T should be ≈ 30 throughout the millimeter region. We will discuss below the problem of avoiding hysteresis under the operating condition required for best performance. A series array of junctions would in principle solve most of these problems and allow the predicted values of T_m/T to be approached[8]. This prediction has not yet been tested experimentally.

Although the performance of the Josephson mixer cannot be understood in terms of a curvature parameter S, it shares some features of large S value mixers, including a low saturation power level. The mixer is badly saturated when the signal power is comparable to $10^{-2}\left(I_c^2 R\right)$ compared with a local oscillator power $\approx I_c^2 R$. It seems plausible that the saturation level would be increased by the use of a high impedance series array of junction since the power per junction would be decreased.

Josephson Effect Mixer with Internal Local Oscillator

The AC Josephson currents in a point contact junction which is biased at a finite voltage have been used as the local oscillator for a millimeter wave heterodyne down-converter[9]. Since the low frequency noise in the junction frequency modulates this local oscillator over many hundreds of MHz, coherent down-conversion of monochromatic signals is not obtained. When used as a receiver for broad band thermal sources, temperature sensitivities $\Delta T <$ 0.3 K were measured in 1 sec from 40 to 260 GHz. This corresponds to a receiver noise temperature $T_R \lesssim 6 \times 10^3$ K. It is thought that this number could be significantly reduced with better coupling of the junction to the RF signal. Although the usefulness of this device is limited by its wide LO bandwidth, the sensitivity is high enough to be interesting, and the

absence of any requirement for a local oscillator leads to great convenience of operation.

Josephson Effect Video Detector

The maximum zero voltage current of a Josephson junction decreases as I_{RF}^2 for $I_{RF} << I_c$. Consequently, if no local oscillator power is applied, a non-hysteretic junction which is biased in the resistive region with a constant bias current will act as a square law detector for small signals[10]. As was the case with the mixer, the complexity of the Josephson effect makes this device quite different from the classical diode rectifier. For signal frequencies ω_s which are low compared with the Josephson frequency set by the bias voltage $\omega_J = 2eV_{bias}/\hbar$, there is classical video detection which is proportional to d^2V_o/dI_o^2. There is a dispersive enhancement and a change of phase when $\omega_s = \omega_J$, and the response is proportional to $R_D = dV_o/dI_o$ for $\omega_s > \omega_J$.

Relatively low impedance junctions, in which the rounding of the I-V curves by fluctuations is not severe, must be resonantly coupled to the RF radiation. Higher impedance junctions are easier to couple to free space radiation, but are dominated by fluctuations[11]. The experiments in both cases are in reasonable agreement with the RSJ model theory and give NEP ≈ 3 to 5×10^{-15} W/$\sqrt{Hz}$ at 90 to 120 GHz. This NEP should scale as Ω^2 at higher frequencies. Some frequency selectivity can be obtained if the junction is biased with a modulated voltage centered around $\hbar\omega_{RF}/2e$. Since the response is dispersive in form, it is only useful for narrow-band signals. The observed NEP for junctions operated in this mode is considerably higher than the values quoted above[12].

Superconducting Bolometer

Thermal (bolometric) detectors have historically been the most sensitive wide band receivers of submillimeter wave radiation. These consist of a radiation absorbing element, a thermometer, and a thermal link to the heat sink. To keep thermal noise and heat capacity to a minimum, sensitive bolometers are operated at pumped ^{4}He (or even ^{3}He) temperatures. In con-

trast to diode video detectors which are in practice limited to a single spatial mode of electromagnetic radiation, the area of a bolometer can be adjusted to couple to any number of modes. The best submillimeter wave bolometers available[13] use an $\sim$ 200 Ohms/$\square$ metal film on a transparent dielectric substrate as an absorbing element, and a superconducting Al film operated near its critical temperature of 1.4 K as the thermometer. Such bolometers have shown sensitivities of NEP = 2×10^{-15} W/$\sqrt{\text{Hz}}$ with areas of 0.08 cm^2 and response times of τ = 50 ms. This NEP can, in principle, be reduced by a factor $\sim$ 3 by decreasing the substrate thickness or increasing its Debye temperature, and a factor in excess of 10 by operating at ^{3}He temperatures. The numbers achieved represent a major recent improvement in performance at submillimeter wavelengths compared to that previously available from monolithic semiconductor bolometers. The primary reasons for the improvement are the increased radiation absorption efficiency, and the low heat capacity.

Parametric Amplifiers

Under a variety of bias conditions, Josephson junction exhibits a nonlinear inductive reactance. If this reactance is pumped from a suitable source, parametric gain can be obtained. Gain is generally observed only if some care is taken to control dissipation at parasitic (unwanted) combination frequencies. If the junction resistance is made large compared with the termination impedance of the parasitic, then the idler is said to be shorted out. In this case no power is dissipated due to current flow at the parasitic frequency. Since junction impedances rarely exceed 20 Ohms, this condition is difficult to meet at microwave frequencies. Alternatively the circuit impedances can be made large compared with the junction resistance. Although this termination is frequently used, it does not prevent dissipation at the parasitic frequency, since currents can still flow and dissipate power in the quasiparticle shunt which is internal to the junction.

Josephson effect paramps can be pumped either externally with a microwave oscillator, or internally by means of the AC Josephson currents. Two classes of parametric amplifiers have been developed which are based on these two approaches. We consider first the externally pumped, and then

the internally pumped paramps.

Externally Pumped Paramp

The best performance of an externally pumped Josephson effect parametric amplifier has been obtained with a doubly degenerate negative resistance mode of operation in which the junction has zero DC (current and voltage) bias. The physical symmetry of a junction which is biased in this manner implies that the nonlinear inductance will depend only on even powers of the current. The amplifier is therefore operated with $2\,\omega_p = \omega_s + \omega_i$ and $\omega_p \approx \omega_s \approx \omega_i$. The lowest parasitic frequencies are at $\approx 3\,\omega_p$ and $\approx 5\,\omega_p$.

Amplifiers of this type have been operated at 10 and 33 GHz using a series array of Dayem bridges[14], at 9 GHz using a series array of tunnel junction[15], and at 36 GHz with a single point contact[16]. Gain in excess of 10 dB is generally obtained if the bandwidth is sufficiently narrow to avoid saturation on external noise[17]. Since the external power which can be carried without saturation increases with the number of junctions employed, the gain bandwidth parameter $G^{\frac{1}{2}}\Delta\omega/\omega$ is larger for the array paramps. Values of 12-15 dB gain with 10 percent bandwidths have been observed at 10 and 33 GHz using arrays of $\sim$ 100 bridges. The dynamic range of these amplifiers is relatively small, and is influenced by parametric oscillations (or amplification of junction noise) in a way which is not well understood. It appears not to be a sensitive function of the number of junctions employed.

The noise measured in this type of paramp has generally been dominated by noise from the (room temperature) circulator and the heterodyne receiver which follows it. In most cases it has only been possible to set an upper limit to the noise expected from an amplifier operated with a cooled circulator. These upper limits typically correspond to $T_N \simeq 20$ to 50 K.

A theoretical model has been used to interpret the array paramp which assumes that all important idlers are shorted[14]. Since each individual junction sees a high impedance RF source, and thus becomes unstable for pump currents in excess of I_c, it appears that the open circuit idler theory[16] may be more appropriate. Based on this theory, the maximum normalized frequency at which such an amplifier can be operated is $\Omega = 0.3$. Although

heating can still be important, some forms of hysteresis on the DC I-V curve do not directly affect this device, since they disappear under the operating conditions in which the zero voltage current is suppressed essentially to zero by the pump.

Attempts have been made to operate an externally pumped Josephson paramp in the singly degenerate mode in which $\omega_s \approx \omega_i \approx \omega_p/2$. Parametric oscillations have been seen in tunnel junctions and point contacts, but not gain[16,18].

Internally Pumped Paramps

Gain has been observed[19,20] at 30 MHz and 9 GHz in an internally pumped singly degenerate parametric amplifier with $\omega_s + \omega_i = \omega_p$ and $\omega_s \approx \omega_i$. The point contact junction was voltage biased in a low inductance (resistive SQUID) configuration so as to provide a voltage-clamped pump at $\omega_p = 2eV/\hbar$. The circuit was resonant at $\omega_s \approx \omega_i$ and short circuited other important combination frequencies. This amplifier closely resembles a conventional type of varactor paramp with a single important idler frequency. It is difficult to provide the required circuit properties for this amplifier at microwave frequencies because of the $\lesssim 10$ Ohm impedance of typical point contacts. A series array of junctions might alleviate this problem, but it would have to be operated in a synchronized, voltage biased mode which has not yet been observed at microwave frequencies.

A more promising type of internally pumped amplifier for high frequency applications has been developed independently by two groups[20,21]. Although the devices appear qualitatively similar, the discussion of them is quite different. One was analyzed as a resistive SQUID without reference to the I-V curve of the contact, and the other was analyzed in terms of the step induced on the measured I-V curve by a cavity which was resonant at ω_s. In both cases, $\omega_p < \omega_s$ and the important idler frequencies are at $\omega_s - \omega_p$ and at $2\omega_p - \omega_s$. The measured value of $G^{\frac{1}{2}}\Delta\omega/\omega$ was only 4×10^{-3} due to coupling limitations for the low impedance junctions employed[21]. The maximum theoretical values are $\lesssim 0.4$ for normalized frequency $\Omega \approx 1$ and $\lesssim (2\Omega)^2$ for $\Omega > 1$. It therefore appears promising for operation at frequencies above 100 GHz. The noise temperature of this amplifier reaches a minimum value

of 42T at $\Omega = 1$. Because of its large noise, this amplifier will be competitive only at relatively high frequencies.

The two idler parametric amplifier discussed above will up-convert signals from the idler at $\omega_s - \omega_p$ to the signal frequency ω_s. When resonated at $\omega_s - \omega_p$ = 115 MHz, it served[20] as a parametric up-converter to 9 GHz with a low noise temperature $\leq$ 3.6 T and a power gain of 25. The relatively large noise in the two idler paramp can be understood in terms of the parametric up-conversion of ambient temperature noise from the low frequency idler at $\omega_s - \omega_p$.

This parametric up-converter can in principle be coupled with a low noise down-converter such as the super-Schottky to provide low noise single frequency amplification. This combination has been proposed as a low noise IF amplifier for a heterodyne receiver based on the super-Schottky heterodyne mixer[22].

Properties of Real Josephson Junctions

The resistively shunted junction (RSJ) model with the full (energy gap limited) value of $I_cR = \pi\Delta/2e$, and thermal noise in the shunt resistor, has generally been used to predict the ultimate performance of high frequency Josephson effect devices. The actual performance of such devices has usually been limited by the (frequently) less favorable properties of real junctions.

For high frequency operation, a large value of the I_cR product is nearly always desirable. This can be obtained with high T_c superconductors under ideal conditions. Clean Nb point contacts have the full theoretical I_cR (except at high impedances) but, unfortunately, are rather unstable. The more stable oxidized Nb point contacts tend to have smaller values of I_cR. Full values of I_cR are generally found in tunnel junctions and variable thickness bridges, where the phase variations are confined to a small region, and not in Dayem or proximity effect bridges.

Devices which must be biased at finite voltage suffer from the general problem that hysteresis appears on the I-V curve of most well-shielded junctions when they are operated at low temperatures and with large values of

I_cR. According to well known models, hysteresis can be caused by internal capacitance, by heating, and by a frequency dependent external impedance. Some progress has been made in understanding the importance of these sources of hysteresis in various types of junctions.

Internal junction capacitance does not generally contribute to hysteresis on the I-V curves of point contacts and thin film bridges, although Josephson plasma resonances in the submillimeter wavelength range are certainly possible. Capacitance certainly dominates the performance of the usual types of evaporated-film, oxide barrier tunnel junctions. Recent work[23] with small area high current density tunnel junctions has shown, however, that their properties are essentially similar to these of point contacts and variable thickness bridges.

Heating appears to be a severe limitation to the performance of the classical Dayem bridge which has uniform film thickness. The characteristic times for excited quasiparticles to relax to the phonons, and for the phonons to escape to the substrate or He bath correspond to low microwave frequencies[24].

Heating effects are reduced if the junction region looks into a large enough solid angle of (superconducting) metal that the excited quasiparticles can diffuse away and be replaced by equilibrium quasiparticles, rather than relax in the junction region. This condition can be met in point contacts, in tunnel junctions with thick metal films, and in variable thickness bridges with thick "banks". Recent experiments with these last structures have shown RF induced steps out to 3.7 mV[25], where the temperature at the center of the bridge has been computed to be $\sim$ 20 K. Steps have been seen out to 17 mV in Nb point contacts[26] which corresponds to a temperature at the center of $\sim$ 100 K. These estimates based on the Wiedemann-Franz law[27] strongly suggest that tunneling through a normal layer plays an important role at high frequencies and/or high voltages, even in three-dimensional point contacts and variable thickness bridges.

An additional source of hysteresis can arise from the effects of the external circuit impedance. If this impedance is very high at all frequencies, then the I-V curve obtained from the RSJ model (without noise or RF bias) is hyperbolic and shows no hysteresis. A reduction of the external impedance (at a given frequency) leads to a depression of the static I-V curve at the corresponding voltage. If the current at the bias point is

depressed below I_c, there will be negative resistance and hysteresis. This effect is easily understood in the limit of zero external impedance at the bias frequency. The pair current then varies sinusoidally in time so that it makes no time average contribution to the total (DC) current. A junction which is used in a high frequency device will usually be tightly coupled to a finite RF source resistance. The static I-V curve will therefore be depressed in the neighborhood of the RF frequency, and negative resistance will occur in the absence of fluctuations (T = 0).

The effects of current fluctuations, which arise from external noise or Johnson noise in the shunt resistance, is to smooth out hysteresis. The noise parameter $\Gamma = 2ekT/I_c\hbar$ is the ratio of an effective fluctuation current to the critical current. As Γ approaches unity it becomes possible to DC bias at any point on the I-V curve. Since the fluctuations also contribute directly to device noise, it is desirable to minimize them by operating in a shielded environment and at low temperatures. There is a tendency for devices which require a stable bias point at finite voltage to have a minimum practical operating temperature, below which hysteresis appears.

It is difficult in practice to distinguish between different sources of hysteresis. Hysteresis from any source grows rapidly as the temperature decreases, since I_c grows and the fluctuation current decreases. For a junction with a constant I_cR product, operating voltage, and temperature, the noise parameter Γ increases in proportion to R. At the same time R grows relative to the external circuit impedance, so that both the hysteresis caused by the external circuit, and the fluctuations which mask it, tend to increase with R. Hysteresis from heating will depend primarily on V (in the three-dimensional Wiedemann-Franz model[28]) or on the dissipated power V^2/R, so will decrease in importance as R, and therefore Γ, increases.

The use of series arrays of Josephson junctions has often been mentioned as a way to improve device performance. Several important advantages can be obtained in this way. The array impedance can be several hundreds of Ohms, so that junction matching is simplified. Each junction in a series array looks out into the high impedance of the other junctions, so that hysteresis arising from the matching circuit should not be a problem in arrays containing many junctions.

The primary difficulty with arrays of junctions is that the spread in junction properties often makes it difficult to obtain the required bias condition. Arrays have been successfully used only in the case of the externally pumped parametric amplifier which requires no DC bias. If series arrays can be made in which most of the junctions have critical currents which differ by only a few percent, they would be useful for such devices as the video detector or the heterodyne mixer with external LO. These require a DC bias, but do not depend critically on the value of the Josephson frequency. Unsynchronized series arrays will not be useful for devices such as internally pumped parametric amplifiers or mixers which require a narrow width of the Josephson oscillations.

Experiments at relatively low frequencies have shown a tendency for closely spaced junctions to synchronize and act coherently[28]. It is speculated that the injection of non-equilibrium densities of pairs and quasiparticles from one junction into its neighbors may cause this effect. If such synchronization could be extended to the microwave frequency range, it would permit the use of arrays in several of the internally pumped devices. Such arrays would couple useful amounts of microwave power into an external circuit. At frequencies low enough (or with arrays small enough) to avoid internal resonances, synchronized arrays might be useful as wide band voltage controlled microwave oscillators.

Conclusions

The future of Josephson effect high frequency devices depends critically on the detailed properties of available junctions. Idealized calculations based on the RSJ model predict useful performance at millimeter and submillimeter wavelengths for many of the devices discussed here. Although some measurements at millimeter wavelengths approach the theoretical performance, many do not.

Difficulties in obtaining large values of I_cR without hysteresis are often mentioned. In some cases these are due to heating and improvement is possible in principle. The fundamental limits to the performance of single junction devices which arise from the coupling to the RF source, however, have not generally been given adequate attention. Although arrays of junc-

tions will in principle alleviate these problems, a major effort will be required to produce arrays with adequate uniformity.

Very similar performance is now being obtained from the best point contacts, variable thickness bridges, and small area tunnel junctions. The properties of all of these structures deviate from the RSJ model in ways which are understandable from the full microscopic theory. The effect on high frequency device performance of such phenomena as subharmonic gap structure, etc, are not generally known. They may be very important, especially for junctions operated with samll Γ. Careful measurements of the high frequency impedance[29] of appropriate types of junctions may be the best way to obtain general answers to these questions.

In the enthusiasm over the Josephson effect, there has been relatively little recent work on non-Josephson superconducting devices. The excellent prospects of the super-Schottky diode and the superconducting composite bolometer show that these possibilities should not be neglected.

The author gratefully acknowledges helpful discussions with many persons including R. Chiao, J. H. Claassen, K. K. Likharev, Y. Taur, and M. Tinkham.

References

†Work supported by the U.S. Office of Naval Research.

1. Richards, P. L.: The Josephson junction as a detector of microwave and far infrared radiation. "Semiconductors and Semimetals", Willardson, R. K., and Beer, A. C. Eds. (Academic Press, New York, to be published) V. 12.
2. McColl, M., Pedersen, R. J., Bottjer, M. F., Millea, M. F., Silver, A. H., and Vernon, F. L. Jr.: The super-Schottky diode microwave mixer. Appl. Phys. Letters 28, 159-162 (1976); McColl, M., Millea, M. F., Silver, A. H., Bottjer, M. F., Pedersen, R. J., and Vernon, F. L. Jr.: The super-Schottky microwave mixer (Proceedings of the 1976 Stanford Applied Superconductivity Conference, to be published).
3. Van Duzer, T., and Huang, C. L.: Schottky diodes and other devices on thin silicon membranes. IEEE Trans. ED-23, 579-583 (1976).
4. Blaney, T., and Knight, D. J. E.: Direct 825th harmonic mixing of a 1 GHz source with an HCN laser in a Josephson junction. J. Phys. D6, 936-952 (1973).

5. Taur. Y., Claassen, J. H., and Richards, P. L.: Conversion gain and noise in a Josephson effect mixer. Rev. Phys. Appl. 9, 263-268 (1974); Conversion gain in a Josephson effect mixer. Appl. Phys. Letters 24, 101-103 (1974); Noise in Josephson point contacts with and without rf bias. Appl. Phys. Letters 25, 759-761 (1974).

6. Claassen, J. H., and Richards, P. L. (to be published).

7. Edrich, J., Sullivan, D. B., and McDonald, D. G.: A low noise Josephson mixer for the 1 mm wavelength range (to be published).

8. Richards, P. L., Claassen, J. H., and Taur, Y.: Josephson effect mm-wave receivers. "Low Temperature Physics - LT14", Krusius, M., and Vuorio, M., Eds. (American Elsevier, New York, 1975) V. 4, pp. 238-241.

9. Avakjan, R. S., Vystavkin, A. N., Gubankov, V. N., Migulin, V. V., Shtykov, V. D.: Millimeter waveband signal conversion in S-c-S Josephson junctions with self-pumping. IEEE Trans. MAG-11, 838-840 (1975).

10. Kanter, H., and Vernon, F. L., Jr.: High frequency response of Josephson point contacts. J. Appl. Phys. 43, 3174-3183 (1972); Response of superconducting point contacts to high frequency radiation. Phys. Letters 35A, 349-350 (1971).

11. Tolner, H., and Andriesse, C. D.: High impedance point contact Josephson junctions. IEEE Trans. MAG-11, 866-869 (1975); Tolner, H., Andriesse, C. D., and Schaeffer, H. H. A.: Wide-band detection with high impedance Josephson junctions. (Proceedings of the 1975 Zürich International Conference on Infrared Physics, to be published).

12. Kulikov, V. A., and Likharev, K. K.: Microwave detection, selfselective mode of operation at 30-40 GHz with Nb point contacts. Izv. VUZOV-Radiofiz. 19 (1976).

13. Clarke, J., Hoffer, G. I., Richards, P. L., and Yeh, N.-H.: A superconducting transition edge bolometer. "Low Temperature Physics - LT14", Krusius, M., and Vuorio, M., Eds. (American Elsevier, New York, 1975) V. 4, pp. 226-229; (and to be published).

14. Parrish, P. T., and Chiao, R. Y.: Amplification of microwaves by superconducting microbridges in a four-wave parametric mode. Appl. Phys. Letters 25, 627-629 (1974); Chiao, R. Y., and Parrish, P. T.: Parametric amplification by unbiased Josephson junctions. J. Appl. Phys. 46, 4031-4042 (1975); Feldman, M. J., Parrish, P. T., and Chiao, R.

Y.: Operation of the Suparamp at 33 GHz. J. Appl. Phys. 47, 2639 (1976).

15. Claeson, T. (private communication).

16. Taur, Y., and Richards, P. L.: Parametric amplification and oscillation at 36 GHz using a point contact Josephson junction. J. Appl. Phys. (to be published); A Josephson effect parametric amplifier at 36 GHz. (Proceedings of the 1976 Stanford Applied Superconductivity Conference, to be published).

17. Feldman, M. J.: The thermally saturated suparamp. (to be published).

18. Mygind, J., Pedersen, N. F., and Sorensen, O. H.: Direct detection of the parametrically generated half-harmonic voltage in a Josephson tunnel junction. (to be published).

19. Kanter, H., and Silver, A. H.: Self-pumped Josephson parametric amplification. Appl. Phys. Letters 19, 515-517 (1971).

20. Kanter, H.: Parametric amplification with self-pumped Josephson junctions. IEEE Trans. MAG-11, 789-793 (1975); Two idler parametric amplification with Josephson junctions. J. Appl. Phys. 46, 4018-4025 (1975).

21. Vystavkin, A. N., Gubankov, V. N., Kuzmin, L. S., Likharev, K. K., Migulin, V. V., and Senenov, V. K.: One frequency parametric amplifier using self-pumped Josephson junction. (Proceedings of the 1976 Stanford Applied Superconductivity Conference, to be published).

22. Silver, A. (private communication).

23. McDonald, D. G., Johnson, E. G., and Harris, R. E.: Modeling Josephson junctions. Phys. Rev. B13, 1028-1031 (1976).

24. Kaplan, S. B., Chi, C. C., Langenberg, D. N., Chang, J. J., Jafarey, S., and Scalapino, D. J.: Quasiparticle and phonon lifetimes in superconductors. (to be published).

25. Octavio, M., Skocpol, W. J., and Tinkham, M.: Improved performance of tin variable-thickness superconducting microbridges. (Proceedings of the 1976 Stanford Applied Superconductivity Conference, to be published).

26. McDonald, D. G., Kose, V. F., Evenson, K. M., Wells, J. S., and Cupp, J. D.: Harmonic generation and submillimeter wave mixing with the Josephson effect. Appl. Phys. Letters 15, 121-122 (1969).

27. Tinkham, M. (private communication).

28. Palmer, D. W., and Mercereau, J. E.: Coherent effects in series arrays

of proximity effect superconducting bridges. IEEE Trans. MAG-11, 667-670 (1975).

29. Claridge, D. E., Giffard, R. P., Michelson, P. F., and Fairbank, W. M.: Nine gigahertz impedance measurements on Ta and Nb point contacts. (Proceedings of the 1976 Stanford Applied Superconductivity Conference, to be published).